STUDIES IN HIGH TEMPERATURE STRESS OF STRAWBERRY AND ALLEVIATION OF STRESS THROUGH EVAPORATIVE COOLING

by

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TABLE OF CONTENTS

Page

Introduction 1

Review of Literature 4

Temperature Studies - General Cultural Practices.. 10

Fruit Study 1

Materials and Methods 12

Results and Discussion 12

Runner Study 1

Materials and Methods 14

Results and Discussion 15

Fruit Study 2

Materials and Methods 17

Results and Discussion 18

Runner study 2

Materials and Methods 19

Results and Discussion 19

Runner study 3

Materials and Methods 20

Results and Discussion 21

Field Study

Materials and Methods 24

Results and Discussion 25

TABLE OF CONTENTS

Greenhouse Study

Materials and Methods 29

Results and Discussion 31

Conclusion 34

Literature Cited 36

Appendix 40

LIST OF TABLES AND FIGURES

Tables

1. Mean berry weight and soluble solids content of strawberries grown at 4 day/night temperature regimes..... 14

2. Mean runner growth of strawberries grown at 4 day/night temperature regimes..... 15

3. Growth chamber temperature regimes..... 17

4. Mean berry weight and soluble solids content of strawberries grown at two temperature regimes..... 19

5. Mean runner growth and number of runners for two temperature regimes over a two week period..... 20

6. Mean daily growth and number of new runners/plant under 3, 6, and 10 days of high temperatures (phase 1), followed by 4 days of moderate temperatures (phase 2)..... 22

7. Mean berry weight, soluble solids content, and firmness of evaporative cooled strawberries in a greenhouse..... 32

Figures

1. Strawberry leaf temperature during and following sprinkler irrigation on August 21, 1987. Air temperature was 35.5°C and relative humidity was 33% 28

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Introduction

The overall purpose of this study was to develop guidelines for evaporative cooling to alleviate heat stress of strawberry (*Fragaria x ananassa Duch.*). Heat stress in plants typically results in reduced photosynthetic rate and increased transpiration rate. This can result in reduced growth, yield, and inferior fruit quality of strawberry plants. In northern regions, high temperatures are typically experienced in mid-to-late summer during runner (stolon) growth and flower bud initiation. In southern states heat stress can also be a problem during bloom and berry development. It is possible that by alleviating heat stress during these critical stages, fruit quality may be improved and vegetative growth enhanced, possibly resulting in higher yields the following spring.

As a first step in developing guidelines for evaporative cooling, critical temperatures that affect berry development and runner growth were investigated. Duration and frequency of water application were studied to develop irrigation scheduling procedures. Proper scheduling of water application would prevent excessive water use, lower cost, decrease the risk of disease problems, and increase production efficiency.

The studies were conducted in three phases beginning in Fall, 1986 and ending in Spring, 1988.

The first phase was designed to identify a critical high temperature that inhibits strawberry growth during fruit and runner development. Two fruit and three runner experiments were conducted under controlled conditions in environmental growth chambers. Because previous studies (Abdelrahman, 1984; Chabot and Chabot, 1977) have shown a critical stress temperature occurring between 30-40°C, day/night temperature treatments ranged from 25/15°C to 40/30°C at 5° increments to determine a more precise temperature at which growth was inhibited. Acclimation to high temperature and resumption of vegetative growth following high temperature stress were also examined.

The second phase was a field study to determine an optimum sprinkling period duration for maximum cooling. Air and leaf temperatures were monitored under various high temperatures and sunlight intensities prior to, during, and after sprinkling periods. The time required to reach the maximum temperature reduction was measured under varying conditions.

The third phase was a greenhouse study to investigate the effect of evaporative cooling during fruit development under high temperature conditions. Evaporative cooling effects were separated from possible irrigation effects by covering the soil with clear plastic to exclude sprinkler applied water from

the soil. Sprinkling duration and critical stress temperatures determined from the previous studies were used to determine the sprinkling cycle.

Literature Review

Plant growth and fruit production are frequently hindered by excessively high air, soil, and plant temperatures (Devlin, 1975). These conditions are further aggravated by intense solar radiation received directly by the plant. Under these conditions, the photosynthetic rate is reduced and the transpiration rate can exceed the ability of the roots to absorb water (Devlin, 1975). This can result in reduced growth, yield, and poor fruit quality (Salisbury and Ross 1978). Even when soil moisture is adequate, there is evidence indicating that the plant can still be under stress during high temperatures (Van Der Brink and Carolus, 1965). Inhibitory temperatures may be different throughout the development of the plant (Went, 1953), and growth inhibition of strawberry due to heat stress may occur at various times during the growing season.

In strawberry, the first 10 days after fruit set are a critical stage; it is a period of cell division in the fruit when growth conditions establish the potential for final fruit size (Darrow, 1966). Yield can also be affected by the extent of runner growth during the previous season because strawberry beds must be reestablished each year. Maximum runner formation was found to occur at a soil temperature of 24^{o}C

(Proebsting, 1957). Optimum air temperatures for runner growth have been reported to occur between 23 and 26°C (Darrow, 1930; Durner, et al., 1984; Smeets, 1955). Abdelrahman (1984) demonstrated that day/night temperatures of 40/30°C completely inhibited runner formation in the cultivars 'Raritan', 'Sparkle', and 'Pocahontas'. The same study demonstrated that berry weight was reduced at day/night temperatures of 30/20°C compared to 20/10°C. It would be useful to identify a more precise critical temperature which inhibits runner growth and berry development, and to learn if the inhibitory effects of temperature are permanent.

In order to reduce the growth inhibitory effect of heat stress, the microenvironment of plants can be modified by the use of sprinkler irrigation. Plant, soil and surrounding air temperatures can be lowered. When water is applied to foliage, leaf temperature is reduced by evaporative cooling. The relative humidity can be increased in the atmosphere surrounding the plant and this can reduce transpiration and plant water loss. Chesness and Braud (1970) demonstrated an average reduction of ambient air temperature (15.24 cm above mulch level) as much as 8.9°C during sprinkling cycles. Strawberry leaf temperatures were reduced by as much as 13.3°C and ground surface temperatures were lowered an average of 4.3 to 6.4°C, depending on duration of

sprinkling time. In another study, temperature of the foliage and air immediately above the leaves was lowered as much as 8.3°C with misting when air temperature was in the 35-37.8°C range and relative humidity about 30% (Middleton and Jensen, 1969).

Air temperature 2.54 cm above the soil surface may be as much as 6.7°C higher in nonirrigated organic soils (Wheaton and Kidder, 1965). High soil temperature can also be detrimental to plant growth and sprinkled soil has been shown to usually remain cooler than flooded soil (Robinson, 1969). Proebsting (1957) has demonstrated that soil temperatures of 45°C decrease growth. Gray (1941) noted that 37.8°C root temperature caused strawberry plants to transpire much less than a root temperature of 29.4°F. However, the reduced transpiration rate was not evident in the first 24 hour period, but was clearly evident in the second 24 hour period. Wilting occurred at root temperature of 37.8°C during the heat of the day and roots stopped normal growth.

Many studies have been done on relieving heat stress through evaporative cooling. Overhead sprinkling of grapevines has lowered air, leaf, fruit, and soil temperatures 5-10°C as opposed to nonsprinkled grapes (Aljibury, et al., 1975). The cooling treatments increased fresh weight of berries and

increased shoot growth. In another study with grapes, evaporative cooling was done with small amounts of water intermittently applied (Gilbert, et al., 1970). Plant temperatures were shown to be reduced 8-11°C.

A study done with 'Delicious' apples using a low volume overtree irrigation system resulted in improved fruit quality and weight, while reducing corking and bitter pit (Unrath and Sneed, 1974). Similar studies with onions (Wright, et al., 1981), muskmelons and cucumbers (Bible, et al., 1968), and tomatoes (Bible, et al., 1968; Van Der Brink and Carolus, 1965), showed increased yields and/or fruit quality with evaporative cooling.

An air temperature reduction of 9°C and leaf temperature reduction of 13°C was achieved by evaporative cooling of strawberry, resulting in increasing yield (Chesness and Braud, 1970). The berries were larger and had better fruit quality that was retained longer. In Wales, a commercial strawberry grower used a low pressure sprinkling system in an attempt to alleviate sun scalding (Valentine, 1980). The sprinkled berries had little loss from sun scalding and were able to develop normally instead of too quickly, which is often a result of heat stress.

In Michigan, mist cooling of strawberries when air temperatures were above 32.2°C and relative humidity

less than 30% resulted in approximately 3027 more liters of berries per acre than in other areas of a field which received the same amount of water divided into two waterings. Berries were larger, brighter, and kept longer (Unrath and Sneed, 1979).

The success of sprinkler irrigation for evaporative cooling is highly dependent on local weather conditions. The rate of water evaporation, and thus the amount of cooling is directly related to the relative humidity, temperature, and wind velocity (Dana, 1981). At 100% relative humidity, no net evaporation occurs and thus there is no cooling effect. At low relative humidities, evaporation is high and thus a considerable cooling effect may be expected. Wind speed also affects evaporation rate and thus influences the benefits obtained from sprinkling (Middleton and Jensen, 1969).

Previous studies have used a variety of methods to schedule and apply water for evaporative cooling (Aljibury, et. al., 1975; Butler, 1984; Carolus, 1964; Gilbert, et. al., 1970; Unrath, 1972; Valentine, 1980). There are, however, a number of unknowns in developing guidelines for evaporative cooling of strawberries. These include: at what temperature to start the system, amount of on/off time, method of control, type of sprinkler, the effect of evaporative cooling on

fruit rot, firmness, soluble solids, and excess soil moisture.

Temperature Studies

General cultural practices

Two fruit and three runner runner studies were conducted in environmental growth chambers. Three midseason Junebearing cultivars were used in all experiments. They were chosen due to their differences in regional adaptation; 'Cardinal' represents a southern cultivar, 'Raritan' a northern cultivar, and 'Redchief' a broadly adapted cultivar. Dormant nursery-grown plants were potted in 15 cm plastic pots. ProMix Bx was the medium used for the first fruit and runner study. A complete Sunshine mix was used for the second fruit and runner study, and a soil, peat, perlite (1:1:1) mix was used for the third runner study. The plants were randomly arranged on the greenhouse benches. Watering was done on an as-needed basis. A fertilizer solution, 20N-20P-20K at 240ppm was applied twice to plants used for the fruit studies: once approximately 3 weeks after planting and again prior to placement in the growth chambers. Plants used for the first and third runner studies received an extra application due to the increased time in the greenhouse.

Light in the growth chambers was supplied by a combination of fluorescent and incandescent bulbs suspended approximately 35 cm above leaf height. The

photosynthetic photon flux density averaged 520-580 microEinstiens/m^2/sec in each chamber. Watering was done as needed.

Fruit studies - Cultural practices

Blossoms were hand pollinated using a small artist's paint brush to ensure good fruit set. Plants that had good fruit set were selected and thinned to one primary and two secondary berries to minimize any effect of fruit load. While the berries were still green, plants were placed in the chambers for an acclimation period with 23/13^{o}C day/night temperatures and a 14 hour photoperiod. Acclimation periods lasted approximately 1 week in the first study and 3 days in the second study. When 50% of the primary berries began to turn pink, high temperature treatments began. Berries were picked when ripe, weighed, and soluble solids (^{o}Brix) measured with a Bausch & Lomb hand-held refractometer.

Runner studies - Cultural practices

Plants used in the first and third runner studies were grown in the greenhouse for approximately 2 months. Blossoms were removed as they appeared. Acclimation periods in the growth chambers lasted 3 days with day/night temperatures of 25/15^{o}C and a 15 hour photoperiod. Plants used in the second runner study were the same as those used in the second fruit

study. At the end of berry harvest, the plants were kept in the chambers for an additional 2 weeks of treatment.

Fruit Study #1

Materials and Methods

Twelve plants of each cultivar were placed in a completely randomized design in each of four treatment chambers. During the one-week acclimation period, growth chamber day/night temperatures were 23/13°C with a 14 hour photoperiod. Day/night temperature treatments were as follows; 40/30, 35/25, 30/20, and 25/15°C. A two-way analysis of variance (ANOVA) with cultivars and temperatures as main effects was used to analyze fresh weight and soluble solids (°Brix) data from primary and secondary berries. Fisher's Least Significant Difference (LSD) test was used to determine differences among means.

Results and Discussion

The main effects of temperature and cultivar were significant for the four parameters studied. Fresh weight of primary and secondary berries was significantly reduced only at the highest (40/30°C) temperature regime (Table 1). Soluble solids content of primary and secondary berries was also affected by temperature with a general reduction as temperature increased (Table 1). Soluble solids content of the

primary berries was significantly lower at the 35°C and 40°C treatments compared to the 25°C and 30°C treatments. Soluble solids content of the secondary berries was also significantly lower at 35°C than at the two lower temperatures, but at 40°C, soluble solids was not significantly different than at 30°C. A possible explanation may be that reduced fresh weight of berries at 40°C caused a higher concentration of soluble solids in these berries.

The substantial reduction in primary and secondary berry weight at 40/30°C, and the significantly lower soluble solids content at 35/25°C indicates a critical high temperature range for strawberry fruit development appears to be between 35°C and 40°C.

Significant differences in berry weight and soluble solids between cultivars were apparent and have been previously reported (Darrow, 1966). However, no cultivar x temperature interactions were found indicating that the cultivars responded similarly to temperature treatments.

Table 1. Mean berry weight and soluble solids content of strawberries grown at 4 day/night temperature regimes.

	Berry fresh wt.(g.)[z]		Soluble solids(°Brix)[z]	
Temp(°C)	Primary	Secondaries	Primary	Secondaries
25/15	15.97 a	10.90 a	9.4 a	8.7 a
30/20	15.96 a	10.98 a	8.1 a	6.9 b
35/25	16.17 a	11.35 a	6.6 b	5.2 c
40/30	14.23 b	8.79 b	7.0 b	6.2 b

[z]Means within columns separated by Fisher's LSD p = 0.05

Runner study #1

Materials and Methods

Ten plants of each cultivar were placed in a completely randomized design in each of four growth chambers. Day/night treatment temperatures were the same as fruit study 1 (40/30, 35/25, 30/20, and 25/15°C). All plants were thinned to one new runner per plant. Following the 3-day acclimation period, initial length of each runner was recorded and daily measurements were taken for 12 consecutive days. After 12 days, temperatures in all growth chambers were set to 40/30°C for an additional 5 days and runners were again measured. Data were analyzed with separate analyses for the 12 day period and 5 day period with ANOVA. The paired t-test was used to determine

differences between the means of the twelve day period and the five day period.

Results and Discussion

In the first part of this study, plants were grown under the four temperature regimes (25/15, 30/20, 35/25, 40/30°C) for 12 days. A significant temperature effect on total runner growth was apparent only at the highest (40/30°C) temperature regime (Table 2).

Table 2. Mean runner growth of strawberries grown at 4 day/night temperature regimes.

Temp. (°C)	Total[z,w] Growth (cm)	Part 1[z,w] Daily Growth (cm)	Part 2[y,w] Daily Growth (cm)	T-test prob lev[x]
25/15	27.21 a	2.26 a	1.99 a	0.03
30/20	29.87 a	2.49 a	0.97 b	0.01
35/25	26.05 a	2.17 a	1.02 b	0.01
40/30	12.47 b	1.03 b	0.54 b	0.01

[z]12 days at four temperature regimes.
[y]5 days all treatments at 40°C
[x]compares daily growth rates of part 1 and part 2.
[w]Means within columns separated by Fisher's LSD, p =.05

Total runner growth and daily growth rate under the 40/30°C treatment were less than half the mean growth observed at the other treatment levels. Therefore, a critical high temperature for inhibition of runner growth is the same as for fruit development, occurring

between 35°C and 40°C.

In part two, all temperatures were increased to 40/30°C for an additional 5 days to determine if pretreatment at any of the 3 lower temperature regimes caused acclimation to higher temperatures. Daily runner growth rate was significantly reduced for all plants previously grown in all 4 temperature treatments during the 5 day 40°C treatment of part two (Table 2). The runner growth rate of plants pretreated at 25°C, however, was significantly greater than the runner growth rate of plants from the other pretreatment temperatures. It appears that pretreatment at 25°C may have caused the plants to acclimate. However, high temperature acclimation generally requires exposure to higher temperatures, closer to the stress temperature (Levitt, 1980). Maximum high temperature acclimation with peas required a temperature of 35°C - 40°C (Levitt, 1980). It would seem unlikely, therefore, that the better growth rate at 40°C of plants pretreated at 25°C would have been due to acclimation, and further discussion would be speculative.

Significant differences in runner growth between cultivars were apparent; however, no cultivar x temperature interactions were found. All cultivars responded similarly to temperature treatments and experienced a significant reduction in runner growth

under the 40/30^{o} temperature treatment.

Fruit study #2

Materials and Methods

Due to inadequate fruit set, only eight plants each of 'Raritan' and 'Cardinal' and seven plants of 'Redchief' were placed in each of two growth chambers. Photoperiod remained at 14 hours, but temperatures in the two chambers were varied during the day to simulate field conditions. One chamber followed a relatively moderate temperature regime; the other was operated at 7.3^{o}C higher temperature from 1:00 p.m. to 5:00 p.m. The temperature regimes of the two chambers are listed in Table 3. A two-way analysis of variance (ANOVA) with cultivars and temperatures as main effects was used to analyze berry weight and soluble solids (^{o}Brix) data.

Table 3. Growth chamber temperature regimes during fruit development period.

Time	Temperature(^{o}C)	
	Control	Treatment
7:00 A.M.	18.3	18.3
9:00 A.M.	23.9	23.9
11:00 A.M.	29.4	29.4
1:00 P.M.	29.4	36.7
5:00 P.M.	23.9	23.9
7:00 P.M.	18.3	18.3

Results and Discussion

No significant differences were apparent in berry fresh weight or soluble solids of primary and secondary berries between the two temperature treatments (Table 4.). No cultivar x temperature interactions were evident indicating that all cultivars responded similarly to temperature treatments. The results suggest that a few hours of high temperature (36.7^{o}C) daily during fruit development may not have a significant detrimental effect on the berries. In fruit study 1, berry weight and soluble solids was significantly reduced in the 35^{o}C - 40^{o}C temperature range after receiving 14 hours of constant high temperature.

Growth chamber conditions can only approximate field conditions. Air, plant, and fruit temperatures are nearly equal under growth chamber conditions; under field conditions, plant and fruit temperatures can be considerably higher due to solar radiation and could remain higher for longer time periods. The length of time plants are subjected to high temperature is of fundamental importance. The longer plants are exposed to high temperatures, the longer it takes them to resume growth (Levitt, 1980).

Table 4. Mean berry weight and soluble solids content of strawberries grown at two temperature regimes.

Temperature regime	Berry fresh wt.(g.)		Soluble solids(°Brix)	
	Primary	Secondaries	Primary	Secondaries
Control	6.95	4.50	8.88	8.98
Treatment	6.87	4.22	8.82	9.27

Runner study #2

Materials and Methods

Following berry harvest in fruit study #2, the plants remained in the growth chambers under the same conditions. All runners that appeared during the fruiting period were removed and the plants were then allowed to runner freely for a two week period. At the end of 2 weeks, runner length and number of runners per plant were recorded. Data were analyzed with the ANOVA.

Results and Discussion

There was no significant difference between treatment and control plants in number of runners emerging during the 2 week period (Table 5). However, total runner growth was significantly reduced when plants were exposed to 4 hours of high temperatures (36.7°C) compared to to the control (29.4°C) (Table 5). This indicates that as little as 4 hours of high temperatures each day can reduce runner growth. This

is in contrast with fruit development which was uneffected by these temperature treatments. Runner growth is apparently more sensitive to short-term high temperatures than berry weight and soluble solids.

The temperature x cultivar interaction was not significant; all cultivars had a significant reduction in runner growth in the treatment chamber. The results confirm the findings of the previous runner growth experiment; growth is inhibited when plant temperature reaches between 35°C and 40°C.

Table 5. Mean runner growth and number of runners per plant for strawberry grown at two temperature regimes over a 2 week period.

Temperature	Mean number of runners	Mean runner growth (mm)*
Control	4.04 n.s.	90.6 *
Treatment	3.08	55.9

* F-test significant, p = 0.05

Runner study #3

Materials and Methods

Ten plants of each cultivar were placed in each of four growth chambers for a 3-day acclimation period. All runners were retained and following the acclimation period, each runner was tagged and initial length recorded. New runners were tagged and measured as they

emerged. After the acclimation period, three of the four growth chambers were operated at 35/25°C for 3, 6, or 10 days, then returned to 25/15°C for 4 days. The fourth chamber served as a control and remained at day/night temperatures of 25/15°C for the duration of the experiment. Runner length was measured at the end of each treatment period (3, 6, or 10 days) (phase 1) and again after the 4 days of lower temperatures (phase 2). Measurements were taken on control plants each time treatment plants were measured. Because no cultivar differences were found, data were pooled for cultivars and analyzed with the paired t-test.

Results and Discussion

Mean daily growth rate of runners was significantly reduced during the first phase of high temperature treatments for 3, 6, or 10 days compared to the control (Table 6).

Table 6. Mean daily growth and number of new runners per plant under 3, 6 and 10 days of high temperatures (Phase 1), followed by 4 days of moderate temperatures (Phase 2).

	Phase 1					
	Mean daily runner growth per plant (mm)			Mean number of new runners per plant		
	3 day	6 day	10 day	3 day	6 day	10 day
Treatment[z]	4.45**	3.95**	3.52**	.344**	.380**	.497**
Control[y]	6.14	6.29	6.69	.781	1.051	1.048
	Phase 2					
Treatment	4.08**	4.62**	3.9**	.271	.366	.249
Control	6.59	7.3	7.79	.335	.384	.298

[z] $35/25^{o}C$
[y] $25/15^{o}C$
**T-test significant $p < 0.01$

The results are similar to runner study 1 and 2 where runner growth inhibition also occurred in the temperature range of 35^{o} - $40^{o}C$. There appeared to be a trend toward greater growth reduction the longer (6 and 10 days) the plants were exposed to the high temperature treatment.

Significant growth inhibition continued in phase two (temperatures lowered to $25/15^{o}C$ for four days). These results suggests that growth inhibition persists for at least 4 days following periods of heat stress. Previous studies have shown that the longer plants are exposed to high temperature, the longer it takes them to resume growth (Levitt, 1980). It should be noted, however, that the high temperature treatments were

applied for 15 consecutive hours with no daily fluctuation which are conditions not often occurring in field-grown strawberries. Also, conditions in growth chambers for plant growth are less than ideal when compared to a natural environment. Light intensity is greatly reduced and root growth and temperature are limited to the conditions of the pot. It is possible that under field conditions resumption of growth could occur within a shorter time span.

Mean number of new runners per plant was significantly reduced at the high temperature regimes compared to control plants during the 3, 6, and 10 day periods (Table 6). However, under the moderate temperatures of phase 2, mean number of new runners per plant in the control decreased to the point where no significant difference with the treatment was apparent. This result was surprising considering that daily growth of the control plants continued at approximately the same rate as in phase 1. Darrow (1966) stated that the more rapidly a strawberry plant grows, the more runners are produced. The reduction in number of runners in the control plants during phase 2 may not be temperature related but further discussion would be speculative. Therefore, the data on high temperature effects on the number of new runners appears to be inconclusive.

Field study

Materials and Methods

Air and strawberry leaf temperatures were monitored under various high temperature conditions prior to, during, and after sprinkling periods to determine an optimum sprinkling duration for maximum cooling.

In a small strawberry field plot (6m x 2.5m) in Manhattan, Kansas, an irrigation system was installed to provide water from two minisprinklers. Water was supplied from a deep well with a temperature of 16°C. The sprinklers were spaced 3 meters apart in the center of the plot and were on a 30.5 cm riser. Each sprinkler delivered a relatively fine droplet size at the rate of 0.15 cm/hr at a pressure of 20 psi, covering a diameter of 6 meters. This system was used for evaporative cooling purposes as well as irrigation of the plot.

The OMEGA CN9000 Series Miniature Microprocessor Controller was used to monitor leaf temperature with a thermocouple attached with cellophane tape to the underside of a mature leaf. When the leaf temperature was at least 35°C, the manually activated sprinklers applied water. The 35°C activation temperature was determined from the previous experiments (fruit study 1, runner studies 1, 2, 3) which showed a critical

range for strawberry plant growth between 35°C and 40°C. Sprinkling continued until it appeared that the leaf temperature would not decrease further. The leaf temperature was recorded every 15 seconds during and after sprinkling periods until the leaf returned to its original temperature prior to sprinkling.

Leaf temperature and sprinkling cycles were monitored in the afternoons on August 21, 25, and September 1, 2, 3, 8, 9, 10, and 14, 1987. Air temperature was monitored every 30 minutes.

Results and Discussion

Maximum air temperatures ranged from 25°C to 37°C on afternoons that sprinkling cycles were monitored. Leaf temperatures in the critical temperature range (35°C-40°C) were observed almost daily. A leaf temperature as high as 48.5°C was recorded on September 14 when the air temperature was 31°C and relative humidity was 62% (Appendix A). Fluctuations in leaf temperature occurred frequently with changes in wind speed and/or clouds temporarily covering the sun. For example, leaf temperature was observed to decrease from 39.2°C to 35.6°C in less than 1 minute on September 14 when clouds temporarily blocked the sun. Air temperature at the time was 31°C and relative humidity was 62%. When a gust of wind blew across the field on September 2, leaf temperature decreased from 40.3°C to

36.7°C in approximately 1 minute. Air temperature was 20°C and relative humidity was 40%. On an overcast day (September 9) when the relative humidity was approximately 54% and air temperature was 28°C, leaf temperature was almost equal to air temperature, fluctuating between 28.7°C and 30°C.

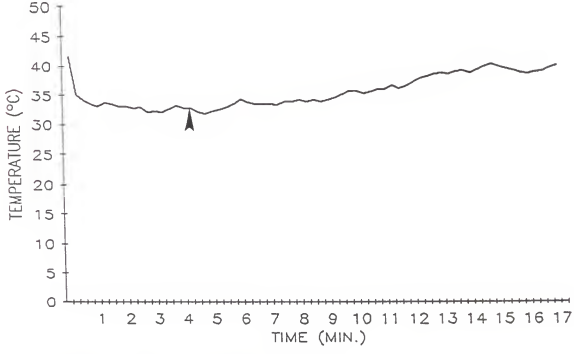
Sprinkler irrigation was effective in lowering the strawberry leaf temperature in a relatively short period of time (Figure 1) (Appendix B). Maximum temperature reduction occurred within the first 3 minutes of sprinkling. Temperature reductions of as much as 15°C were observed when relative humidity was 29% and wind speed approximately 5.3 meters per second. Part of the cooling effect was due to the temperature of the water (16°C), but prolonged temperature reductions were most likely due to evaporative cooling. The amount of leaf temperature reduction and the duration varied considerably depending on climatic conditions. An increase in wind speed, or clouds blocking the sun's rays for a few minutes, would lower the leaf temperature further and increase the duration of the temperature reduction. The duration of leaf temperature reduction varied considerably ranging from 7 to 30 minutes.

This study indicates that sprinkler irrigation can be effective in reducing leaf temperature and

theoretically reduce growth inhibition due to high temperatures. However, irrigation scheduling for evaporative cooling may be difficult. Although leaf temperature, rather than air temperature, appeared to be a better indicator of the need for stress alleviation, there is considerable variability in leaf temperature depending on position in the canopy and angle to the sun. Keeping the thermocouple wire attached to the underside of the leaf also proved to be difficult.

To schedule sprinkling for efficient evaporative cooling, many climatic factors such as wind speed, relative humidity, degree of cloudiness, and air temperature, must be taken into consideration. The manager must also be concerned with the possible effects of excess moisture applied to the fruit, foliage, and soil. Furthermore, it is possible that effectiveness of sprinkler irrigation may decline with greater frequency of use because of increased relative humidity reducing evaporative cooling.

Figure 1. Strawberry leaf temperature during and following sprinkler irrigation on August 21, 1987. Air temperature was 35.5°C and relative humidity was 33%.



Sprinklers turned off after 4 minutes.

Greenhouse study

Materials and Methods

This study examined the effect of evaporative cooling during fruit development under high temperature conditions. Because high temperature conditions seldom occur in the early spring during fruit development in Manhattan, Kansan, and because it was impossible to separate cooling from irrigation effects, this study was conducted in a greenhouse.

Two 1.8 m x 1.2 m x 0.2 m wooden flats were constructed with an 18 x 16 mesh screen placed on the bottom. The flats were placed on a greenhouse bench and filled with a medium consisting of soil:peat:perlite in a 1:1:1 ratio. On April 29, thirty-eight strawberry plants of the cultivar 'Redchief' were planted 20 cm apart in each flat and immediately watered in.

A drip irrigation system was installed in each flat and clear plastic was placed over the soil beds surrounding the plants. Plastic tape was used to seal the holes around the plants as much as possible. Both flats were irrigated with equal volumes of water with a drip irrigation system. Each flat had 18 drip emitters with an average output of 58.2 ml/min. at an approximate pressure of 3 psi. Irrigation was done as needed, and blossoms were hand-pollinated beginning on

May 29.

A minisprinkler was placed in the center of one of the flats. Using the Omega CN9000 series microprocessor controller, leaf temperature was monitored using a thermocouple attached to the underside of a mature leaf. The experimental treatment began on May 23 when a majority of the berries were at the immature green stage. The controller activated a 30 minute timer when the leaf's temperature reached 35°C. The timer was set for a 1 minute on and 6.5 minute off cycle. During the on part of a cycle, a solenoid valve was activated and the sprinkler would apply water.

To simulate field conditions in the greenhouse, a single 9 inch oscillating fan was placed approximately 1.2 meters from each flat to provide air flow with wind speed of 1.1 meters per second. Water was shut off to the greenhouse cooling pads during the experiment to maintain air circulation, but avoid increasing relative humidity. Air temperature in the greenhouse ranged from 21°C in the morning to 32°C in late afternoon. For several hours each day from May 24 through May 27, sprinkling cycles and changes in leaf temperature were recorded every 15 seconds. Air temperature was recorded every 30 minutes.

When ripe, berries were harvested, weighed, and

measured for firmness and soluble solids. Firmness was measured using a Hunter Spring Mechanical Force Gauge (Series L; 0-5N range) with a 3 mm diameter rod as described by Shaw, et al., 1987. The force required to press the rod approximately 1 cm into the fruit was measured and recorded. Two readings were taken per berry and the mean recorded. Percent soluble solids were measured using a hand-held refractometer. Data were analyzed using ANOVA.

Results and Discussion

Air temperatures on days that sprinkling was observed ranged between 27°C and 32°C (Appendix C). Leaf temperatures were generally in the critical temperature range (35°C - 40°C) determined from previous studies. Leaf temperature in the greenhouse fluctuated only 2 or 3 degrees, in contrast to the field where leaf temperature fluctuated as much as 10°C.

During sprinkling cycles, leaf temperature reductions ranged from 2.5°C to a maximum temperature reduction of only 8.2°C, approximately one-half of the maximum temperature reduction that occurred in the field trials.

There were no significant differences between the sprinkled berries and the unsprinkled berries in fresh weight or soluble solids (Table 7). However, the

unsprinkled berries were significantly firmer (Table 7) than the sprinkled berries, which were wet most of the time.

These results are contrary to the reports from field studies in which evaporatively cooled berries were larger, brighter and had better storage characteristics (firmness?)(Chesness and Braud. 1970; Unrath and Sneed, 1979).

Table 7. Mean berry weight, soluble solids content, and firmness of evaporative cooled strawberries in a greenhouse.

Treatment	Berry fresh wt.(g)	Soluble solids (^{o}Brix)	Firmness (Newtons)[z]
Sprinkled	5.19	6.45	0.95 *
Unsprinkled	5.11 n.s.	6.25 n.s.	1.09

* F-test significant, p = 0.05.

The reason for these conflicting results appears to be due to the unsuitable conditions in the greenhouse for evaporative cooling. The low wind speed from the fan (1.1 meters per second) and the typically high (between 55% - 60%) relative humidity kept evaporative cooling to a minimum, causing the berries to remain wet longer. It is known that in warm, rainy weather, strawberries may absorb water through the skin and become soft (Darrow, 1966). In contrast to our experimental

conditions, the field study by Unrath and Sneed (1979) was conducted under conditions of less than 30% relative humidity.

Conclusion

The overall purpose of this study was to develop guidelines for evaporative cooling to alleviate heat stress of strawberry and possibly improve growth, yield, and fruit quality. As a first step in developing guidelines for evaporative cooling, critical temperatures that affect berry development and runner growth were investigated. Results indicate critical high leaf temperatures that inhibit strawberry runner growth and berry development occur between 35°C-40°C. Following a return to moderate temperatures, runner growth inhibition persisted for several days. Even as little as 4 hours of high temperature each day significantly reduced runner growth. Acclimation to critical high temperatures did not occur following pretreatments at 30, 35, and 40°C. However, runner growth rate from plants pretreated at 25°C was significantly greater than runner growth rate of plants from the other pretreatment temperatures.

Air temperature proved to be an inadequate indicator of the need for stress alleviation. Plant and air temperatures may vary considerably, depending on environmental and plant conditions. In field trials, the leaf temperature fluctuated constantly depending on the degree of cloudiness and wind speed. At times, leaf temperature were as much as 17.5°C

higher than air temperature on sunny days. On cloudy days, plant and air temperatures were almost equal.

Sprinkler irrigation was effective in lowering strawberry leaf temperature and theoretically alleviating heat stress. Leaf temperatures were reduced by as much as 15°C on a day when relative humidity was 29% and wind speed averaged 5.3 meters per second. Maximum temperature reductions occurred within the first three minutes of sprinkling. Sprinkling for longer time periods did not further decrease the leaf's temperature. The immediate drop in temperature within the first minute was apparently due to the temperature of the water (16°C). However, amount of temperature reduction and duration varied with changes in wind speed, degree of cloudiness and relative humidity. In the greenhouse, the higher relative humidities (55%-60%) and lower wind speed (1.1 meter per second), kept evaporative cooling to a minimum. Berries remained wet longer, resulting in a reduction in berry firmness.

Scheduling sprinkler irrigation for evaporative cooling should be based on monitoring the leaf temperature rather than air temperature. Sprinkling should begin when the leaf temperature is in the critical temperature range of 35°C to 40°C. For sprinkling to be effective, environmental conditions should be favorable (low relative humidity and good air

circulation) for evaporation to occur. Intermittent sprinkling should be used. Sprinkling for longer than 3 minutes does not appear to be necessary. If sprinkling durations were longer, it is possible that relative humidity of the microclimate could be raised enough to limit evaporative cooling. Furthermore, excess water on fruit and foliage may lead to reduced firmness, fruit rots, and other diseases.

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Appendix A Strawberry leaf temperature variation, 1987.

Date	Sept. 2	Sept. 3	Sept. 8
Time	3:15PM	2:45PM	2:30PM
Air Temp.	29°C	29.5°C	24.2°C
Relative Humidity	39%	50%	50%

Time		LEAF TEMPERATURE (°C)		
Min.	Sec.			
	0	41.6	34.3	33.8
	15	41.8	33.2	34.5
	30	41.7	33.1	35.8
	45	40.6	34.2	36.7
1		40.3	33.4	33.6
	15	39.9	33.5	34.5
	30	39.3	33.3	34.1
	45	39.6	34.5	34.0
2		40.1	34.3	33.4
	15	40.2	33.9	35.0
	30	40.4	34.3	34.2
	45	40.5	33.6	34.1
3		40.2	33.7	35.0
	15	39.5	33.6	35.1
	30	39.9	34.2	34.3
	45	39.8	34.5	35.4
4		39.6	32.7	36.0
	15	38.3	32.2	34.8
	30	38.5	33.0	34.6
	45	39.2	33.4	34.9
5		39.8	34.5	35.1
	15	40.1	35.3	
	30	40.3	35.3	
	45	39.6	35.8	
6		39.1	36.1	
	15	38.2	35.9	
	30	37.8	36.1	
	45	36.7	35.1	
7		36.8	35.6	
	15	37.1	35.8	
	30	37.7	35.8	
	45	37.6	35.0	
8		38.4	35.2	
	15	39.1	35.1	
	30	38.8	36.4	
	45	38.5	37.1	
9		37.8	36.8	

	15	37.0	36.4
	30	37.2	36.1
	45	37.2	36.2
10		37.5	34.9
	15	38.3	
	30	38.9	
	45	39.1	
11		39.2	
	15	38.9	
	30	39.3	
	45	37.8	
12		38.2	
	15	38.4	
	30	39.0	
	45	39.5	
13		40.1	
	15	40.2	
	30	38.7	
	45	39.5	
14		40.2	
	15	40.4	
	30	40.5	
	45	40.3	
15		40.4	

Date	Sept. 9	Sept. 10	Sept. 14
Time	2:10PM	2:00PM	2:00PM
Air Temp.	28°C	25°C	31°C
Relative Humidity	54%	-	62.3%

LEAF TEMPERATURE (°C)

Time Min.	Sec.			
	0	29.6	32.8	44.3
	15	29.6	32.0	45.7
	30	29.9	33.4	45.4
	45	30.0	33.6	46.4
1		28.7	33.4	46.1
	15	28.8	33.6	46.1
	30	29.1	33.6	44.8
	45	29.5	34.4	43.5
2		30.3	35.0	43.1
	15	30.2	34.5	42.2
	30	29.4	34.3	41.3
	45	29.9	33.8	41.0
3		30.0	34.5	40.9

	15	30.7	35.6	40.9
	30	30.5	36.4	41.0
	45	29.8	36.8	40.3
4		30.5	37.2	39.7
	15		37.6	39.8
	30		37.8	39.2
	45		37.5	39.2
5			37.8	37.5
	15		36.8	36.2
	30		37.7	35.6
	45		37.3	35.4
6			36.8	36.3
	15		37.2	36.6
	30		35.8	36.7
	45		37.1	36.4
7			38.3	36.2
	15		36.2	36.2
	30		35.1	36.8
	45		35.4	40.5
8			35.5	43.2
	15		36.4	45.2
	30		36.1	46.5
	45		34.8	47.6
9			35.0	47.7
	15			48.4
	30			48.5
	45			48.0
10				47.9

Appendix B Leaf temperature during sprinkling cycles, 1987.

Date	Aug. 21	Aug. 25	Sept. 1
Time	1:00PM	2:00PM	2:30PM
Air Temps.	35.5°C	34°C	30°C
Relative Humidity	33%	34%	43%

Time		LEAF TEMPERATURE (°C)		
Min.	Sec.			
	0	41.5*	42.0*	39.4*
	15	35.0	39.8	35.2
	30	34.0	36.5	31.8
	45	33.3	34.4	31.2
1		33.0	33.6	31.1
	15	33.6	33.8	29.5
	30	33.3	32.9	29.9
	45	33.0	32.1	30.6
2		32.9	33.2	30.7
	15	32.7	32.4	30.6
	30	32.8	33.4	31.1
	45	32.0	34.0	31.1
3		32.1	34.5	29.0
	15	32.0	34.5	28.9
	30	32.6	34.0	29.0
	45	33.1	32.9	28.7
4		32.7^	32.1	28.5
	15	32.0	30.7	28.7
	30	31.7	30.2	28.6
	45	32.2	29.6	28.7
5		32.4	29.7	29.3
	15	32.8	29.4	29.7
	30	33.3	29.3	30.4
	45	34.2	29.5	31.1
6		33.7	29.3	30.3
	15	33.3	28.9	29.6
	30	33.4	29.0	31.1
	45	33.4	29.1	32.2
7		33.2	29.0	31.9^
	15	33.8	29.2	31.0
	30	33.8	29.7	31.6
	45	34.1	29.6	30.5

* Sprinklers turned on.
^ Sprinklers turned off.

8		33.8	29.6^	29.2
	15	34.1	29.6	29.1
	30	34.5	29.7	28.6
	45	35.0	30.1	28.3
9		35.5	30.5	29.2
	15	35.5	30.6	29.5
	30	35.2	31.0	29.2
	45	35.4	30.7	30.0
10		35.9	31.0	30.6
	15	35.9	30.7	31.2
	30	36.5	30.5	32.9
	45	36.0	30.0	34.8
11		36.4	30.0	35.6
	15	37.0	30.6	36.0
	30	37.8	30.8	36.3
	45	38.0	31.2	36.6
12		38.4	30.9	37.0
	15	38.6	31.5	36.8
	30	38.5	31.4	36.8
	45	38.8	31.3	37.1
13		39.0	31.5	37.4
	15	38.6	31.1	37.3
	30	39.1	31.2	37.9
	45	39.6	31.6	38.4
14		40.1	31.0	38.2
	15	39.9*	30.7	38.7
	30	37.0	31.2	39.1
	45	34.5	31.6	39.1
15		34.1	31.7	39.4
	15	34.6	32.2	39.5
	30	34.2	32.9	39.5*
	45	-	32.8	37.3
16		33.8	33.3	34.7
	15	33.0	32.5	33.3
	30	33.4	32.5	31.6
	45	33.4	33.0	30.7
17		32.5	33.0	31.7
	15	32.1	32.9	32.5
	30	32.2	33.0	32.1
	45	32.1	32.9	31.3
18		33.2	33.6	29.5
	15	-	33.6	29.4
	30	-	33.7	31.1
	45	-	34.1	31.9
19		33.6	33.8	31.8
	15	33.0^	34.1	31.6
	30	32.9	34.3	31.6^
	45	33.4	35.3	31.8
20		33.2	35.5	31.7
	15	32.7	34.4	31.9
	30	32.7	34.9	31.5
	45	33.2	35.2	31.6

21		32.9	36.3	31.5
	15	32.1	37.1	31.2
	30	32.1	36.9	30.7
	45	32.0	35.2	30.8
22		32.5	34.9	31.3
	15	31.9	34.7	32.3
	30	31.7	34.1	31.9
	45	31.8	34.7	31.4
23		31.1	34.5	32.0
	15	31.4	34.5	32.4
	30	31.4	34.5	33.2
	45	31.6	34.1	34.1
24		31.8	34.5	34.3
	15	32.4	34.1	34.3
	30	32.5	34.6	35.2
	45	32.0	35.1	35.4
25		32.7	34.6	36.5
	15	33.4	35.2	36.8
	30	33.2	35.5	37.0
	45	32.8	35.3	36.7
26		33.0	35.0	36.4
	15	33.3	35.0	36.7
	30	33.1	35.1	37.6
	45	32.8	35.1	38.1
27		32.4	35.2	38.0
	15	31.9	34.9	38.7
	30	32.0	35.8	38.5
	45	32.4	35.9	38.6
28		32.2	35.4	38.6
	15	32.8	35.4	39.0
	30	33.0	36.8	39.1
	45	33.1	36.2	-
29		33.1	36.9	-
		33.3	36.6	-
	15	33.2	36.7	-
	30	32.9	36.9	39.5
	45	32.7	38.2	39.5*
30		32.6	37.7	37.5
	15	32.4	37.4	34.0
	30	32.2	37.0	32.8
	45	32.3	36.7	31.2
31		32.4	36.8	31.1
	15	32.4	36.7	30.2
	30	32.6	36.6	29.9
	45	32.6	37.9	30.2
32		33.0	39.0	30.1^
	15	33.3	38.8	31.5
	30	33.2	38.9	31.6
	45	32.9	37.9	31.0
33		32.9	36.6	30.5
	15	32.5	36.8	30.6
	30	32.4	35.1	31.9

	45	32.5	36.4	30.7
34		32.4	37.0	29.5
	15	32.1	36.7	30.1
	30	32.5	36.2	31.8
	45	32.6	35.2	33.3
35		32.4	35.5	32.3
	15	32.2	35.6	31.7
	30	32.3	37.0	31.6
	45	32.7	37.3	31.9
36		32.4	38.3	31.9
	15	32.6	38.3	32.7
	30	32.8	37.2	34.0
	45	32.8	37.2	35.5
37		33.4	37.1	35.9
	15	33.3	37.4	37.0
	30	32.8	37.3	38.2
	45	32.1	37.3	38.6
38		31.9	38.4	37.3
	15	31.9	38.1	37.9
	30	32.3	37.6	38.6
	45	33.4	38.8	39.1
39		33.5	38.8	39.5
	15	33.3	38.4	39.4*
	30	32.7	37.5	37.5
	45	33.0	36.9	35.2
40		32.7	37.9	34.3
	15	32.4	38.4	32.9
	30	32.9	38.8	32.2
	45	33.3	39.0	32.3
41		32.4	38.7	32.6
	15	32.7	36.9	32.4
	30	32.0	37.3	31.5
	45	32.5	37.7	30.9
42		31.4	38.2	30.6
	15	31.4	36.9	30.8
	30	32.4	36.3	31.1
	45	32.4	36.3	32.5
43		32.7	36.0	33.2
	15	32.0	36.1	33.1
	30	32.5	36.0	32.9
	45	-	36.0	32.6
44		-	35.9	32.8^
	15	-	35.8	32.7
	30	-	36.3	32.4
	45	33.3	35.9	32.4
45		33.0	36.3	32.3
	15	32.4	35.7	31.6
	30	-	35.0	31.7
	45	-	35.3	31.4
46		-	36.2	31.7
	15	-	35.8	32.0
	30	33.2	36.2	33.0

	45	32.4	36.2	32.8
47		32.7	35.7	32.5
	15	32.5	34.9	32.4
	30	33.3	34.4	33.2
	45	35.0	34.5	32.1
48		37.2		31.5
	15	38.9		32.7
	30	40.0		33.1
	45	40.1		34.1
49		(44.0)*		34.6
	15	35.5		36.2
	30	32.1		37.0
	45	30.5		36.9
50		31.1		37.7
	15	32.0		39.0
	30	29.7		39.5
	45	30.2		39.8
51		30.9		40.1*
	15	31.6		39.3
	30	-		38.2
	45	-		35.9
52		27.8		33.4
	15	28.3		32.6
	30	28.9		33.3
	45	29.4		34.6
53		29.9		33.8
	15	29.3		31.2
	30	26.4		30.4
	45	26.6		30.9
54		26.6		31.8
	15	26.8		31.8
	30	27.6		31.9
	45	27.5		32.2
55		27.7		32.2
	15	-		32.3
	30	-		33.2
	45	26.9		31.9
56		27.1^		31.6
	15	28.8		
	30	28.8		
	45	29.0		
57		30.0		
	15	31.3		
	30	31.8		
	45	32.7		
60		33.6		
	15	33.9		
	30	34.3		
	45	35.8		

{ } Moved thermocouple to new leaf.

61		36.6
	15	37.0
	30	37.2
	45	37.3
62		37.1
	15	37.2
	30	37.9
	45	38.2
63		37.8

Date	Sept. 2	Sept. 3	Sept. 8
Time	2:30PM	2:00PM	2:30PM
Air Temps.	29°C	29.5°C	25°C
Relative Humidity	40%	50%	50%

LEAF TEMPERATURE (°C)

Time Min.	Sec.			
	0	44.0*	36.0*	35.0*
	15	41.9	34.6	34.2
	30	39.3	33.0	31.5
	45	35.9	30.6	31.2
1		35.1	28.8	30.1
	15	34.8	29.8	29.9
	30	33.2	29.0	29.7
	45	31.9	28.3	29.5
2		31.0	27.9	29.1
	15	30.3	27.8	28.3
	30	28.9	27.9^	28.3
	45	29.4	28.7	28.6
3		30.3	28.2	27.2
	15	30.5	27.9	27.9
	30	31.1	28.1	28.6
	45	31.0	28.7	27.7
3		30.5	28.1	26.7
	15	30.3	28.2	26.8
	30	30.9	27.9	27.9
	45	32.2	28.9	27.9
4		-	28.3	27.2
	15	31.7	28.6	27.3
	30	30.2	29.9	27.9
	45	29.6	28.9	29.0
5		29.9^	29.6	28.7
	15	29.2	30.3	28.2

	30	28.8	30.4	28.4
	45	28.8	31.1	27.8
6		28.2	30.9	27.0
	15	28.6	30.2	27.8
	30	29.0	30.9	28.1
	45	30.4	31.2	27.8
7		31.7	31.0	27.8^
	15	32.5	31.0	27.9
	30	31.3	31.0	26.9
	45	31.0	30.9	25.9
8		31.8	31.2	25.4
	15	32.4	31.1	24.7
	30	32.8	30.6	24.5
	45	32.8	30.5	25.2
9		32.6	31.8	26.0
	15	32.3	32.6	27.0
	30	33.2	31.3	27.6
	45	34.1	31.5	27.6
10		35.0	30.9	27.8
	15	36.3	31.5	28.6
	30	37.2	31.3	29.3
	45	37.8	31.7	29.3
11		38.4	31.9	29.5
	15	39.0	31.2	29.6
	30	39.9	31.0	29.9
	45	40.4	31.6	30.0
12		40.6	32.9	30.0
	15	40.2	33.9	30.0
	30	39.8	34.3	30.4
	45	40.3	33.4	30.5
13		40.8	33.8	31.2
	15	40.1	33.4	31.0
	30	39.0	33.5	30.7
	45	38.4	-	30.4
14		38.7	34.4	31.2
	15	-	34.3	31.2
	30	37.5	34.4	31.5
	45	38.4	35.2*	31.0
15		38.8	34.5	31.4
	15	39.3*	33.3	30.4
	30	39.1	30.9	29.9
	45	38.4	29.9	30.2
16		36.5	28.9	30.6
	15	34.5	28.8	30.7
	30	34.6	29.2	31.7
	45	32.6	-	32.4
17		32.3	30.3	32.9
	15	33.4	29.8	33.5
	30	33.7	29.9	33.1
	45	33.3	28.6	31.9
18		32.8	28.5	31.2
	15	32.7	28.5	31.8

	30	32.2	29.3	31.6
	45	32.3^	29.2	32.9
19		33.0	29.7	33.2
	15	33.3	30.6	32.0
	30	32.4	29.5	30.6
	45	32.9	28.4	30.5
20		32.8	28.4	30.2
	15	32.2	28.8	29.7
	30	31.7	29.6	28.4
	45	32.2	30.2	28.7
21		32.6	30.1	29.7
	15	31.7	30.0	30.7
	30	30.0	28.8	31.0
	45	30.0	28.7	32.1
22		29.9	30.0^	32.7
	15	30.3	30.5	32.7
	30	30.4	30.9	33.3
	45	30.6	31.4	34.5
23		31.6	31.0	35.0*
	15	32.3	30.9	34.6
	30	33.4	30.5	31.4
	45	33.6	30.0	30.6
24		34.1	29.9	30.3
	15	33.8	30.0	29.5
	30	32.9	29.3	28.0
	45	33.1	30.0	28.4
25		33.4	30.7	28.1
	15	33.5	31.0	27.1
	30	32.9	32.1	28.0
	45	33.2	32.1	28.4
26		32.5	33.1	27.7
	15	32.0	33.1	27.1
	30	31.6	33.4	27.3
	45	31.7	33.8	27.1^
27		32.2	35.0	27.4
	15	32.2	34.4	26.9
	30	33.0	33.8	25.7
	45	33.7	32.6	26.1
28		33.4	32.4	26.7
	15	33.3	32.4	27.9
	30	34.2	32.1	28.2
	45	34.5	33.0	28.2
29		33.7	33.6	29.0
		34.4	33.3	29.9
	15	34.6	-	30.0
	30	35.2	-	30.2
	45	34.3	-	30.3
30		34.7	-	29.7
	15	35.6	-	28.1
	30	35.5	33.3	27.9
	45	35.2	34.0	28.2
31		34.0	33.3	27.6

	15	-	33.2	27.3
	30	-	33.0	27.6
	45	-	32.9	28.2
32		33.6	32.4	29.2
	15	34.6		29.5
	30	36.1		30.0
	45	37.0		30.3
33		38.1		30.2
	15	38.5		30.1
	30	38.7		30.3
	45	38.8		30.2
34		38.9		29.4
	15	39.0		29.5
	30	39.7		28.0
	45	41.3*		27.9
35		40.5		28.5
	15	38.8		28.9
	30	37.3		28.7
	45	36.1		28.4
36		35.5		28.9
	15	35.2		29.6
	30	34.7		29.3
	45	34.7		29.2
37		33.3		29.9
	15	32.5		29.9
	30	32.7		30.1
	45	32.3		30.1
38		32.4^		29.4
	15	33.8		29.1
	30	33.3		29.3
	45	33.6		29.3
39		34.2		29.5
	15	34.2		30.0
	30	34.5		29.6
	45	34.7		28.1
40		34.5		28.9
	15	34.8		29.4
	30	35.6		28.7
	45	35.7		29.5
41		35.1		30.0
	15	35.0		28.7
	30	35.0		28.8
	45	34.8		29.4
42		34.7		30.3
	15	35.3		30.7
	30	34.6		30.5
	45	34.2		30.7
43		35.0		29.6
	15	35.2		29.5
	30	35.0		29.6
	45	34.7		29.7
44		33.9		29.3

	15	32.9	28.7
	30	32.2	28.4
	45	32.5	28.3
45		33.3	28.2
	15	35.0	28.1
	30	35.5	29.2
	45	35.9	29.3
46		35.9	29.2
	15	35.8	29.2
	30	35.4	29.8
	45	36.3	29.8
47		36.1	30.5
	15	35.6	30.6
	30	35.1	29.8
	45	35.5	29.7
48		35.7	29.9
	15	36.4	30.7
	30	37.2	-
	45	37.6	31.4
49		38.3	31.5
	15	38.2	30.5
	30	38.8	30.4
	45	38.1	30.7
50		37.7	31.4
	15	37.6	30.6
	30	36.5	29.9
	45	36.3	30.4
51		36.4	31.2
	15	36.9	32.6
	30	36.7	32.4
	45	36.8	32.5
52		37.0	32.7
	15	36.7	32.6
	30	37.6	32.1
	45	38.2	31.4
53		37.9	31.6
	15	37.4	31.4
	30	37.8	32.1
	45	38.5	-
54		-	32.7
	15	39.6	32.5
	30	-	31.8
	45	39.8	31.1
55		40.4	30.9
	15	40.7	31.6
	30	40.6	30.8
	45	39.6	31.3
56			-
	15		31.4

Date	Sept. 9	Sept. 10	Sept. 14
Time	2:20PM	2:15PM	2:15PM
Air Temps.	28°C	26°C	31°C
Relative Humidity	54%	-	62%

LEAF TEMPERATURE (°C)

Time Min.	Sec.			
	0	32.7*	36.5*	48.0*
	15	31.9	36.4	47.4
	30	30.3	34.7	43.1
	45	29.1	33.1	39.8
1		27.9	32.6	39.1
	15	26.8	33.0	37.1
	30	26.7	33.3	34.6
	45	26.8	33.1	33.8
2		25.9	31.7	33.1
	15	26.6	30.6	32.5
	30	26.3	30.0	31.6
	45	26.3	30.5	31.4
3		26.2	31.0	31.8
	15	26.0	31.3	32.3
	30	26.2	31.1	32.6
	45	26.6	29.9	33.0
4		26.6^	29.4	32.9
	15	27.1	30.7	34.3
	30	27.3	30.7	36.4
	45	27.5	29.1	36.8
5		27.4	28.1	37.6
	15	27.3	27.6	37.1
	30	27.1	26.8	-
		26.9	26.0	33.6
6		26.7	26.0	33.1
	15	27.0	25.9	32.8
	30	26.6	25.3	31.8
	45	26.7	25.6	31.0
7		26.2	25.7	31.2
	15	25.1	25.9	30.8
	30	25.5	26.0	30.0
	45	26.1	25.9	29.9
8		26.1	25.9^	30.0^
	15	26.0	25.7	31.2
	30	25.4	25.7	30.5
	45	26.1	25.8	31.8
9		24.6	26.0	34.2
	15	24.9	25.8	35.0
	30	25.4	26.2	35.7

	45	27.0	25.7	35.2
10		27.6	25.8	35.4
	15	28.5	25.4	35.3
	30	29.1	25.7	35.9
	45	28.0	26.1	35.2
11		27.7	25.8	37.0
	15	27.1	26.1	36.7
	30	27.2	25.9	36.4
	45	27.4	26.0	36.3
12		28.2	26.1	36.8
	15	27.5	26.1	36.8
	30	27.6	25.6	36.3
	45	28.6	26.3	35.9
13		29.2	27.3	35.6
	15	29.1	28.2	34.8
	30	29.6	30.1	35.6
	45	30.2	30.9	36.2
14		29.1	31.5	37.0
	15	27.8	32.1	37.5
	30	27.9	32.4	-
	45	27.7	33.3	-
15		29.6	34.3	37.0
	15	30.4	34.0	{40.0}*
	30	31.0	33.7	35.0
	45	-	{36.8}*	33.9
16		31.2	35.8	32.4
	15	32.0	34.6	31.7
	30	32.2	33.1	31.3
	45		32.7	31.5
17			33.5	31.7
	15		33.2	31.8
	30		33.3	31.8
	45		33.5	31.6
18			32.8	31.9
	15		32.7	32.6
	30		32.3	32.7
	45		31.7	32.1
19			31.6	32.0
	15		31.1	31.4
	30		31.5	31.6
	45		31.5	31.4
20			31.9	31.2
	15		31.6	31.5
	30		30.1	31.9
	45		30.5	31.6
21			30.2	30.6
	15		30.4	30.5
	30		30.9	31.2
	45		31.3	30.8
22				

{ } Moved thermocouple to new leaf.

22		30.4	30.6
	15	30.4	30.3
	30	30.2	29.8
	45	30.0	28.7
23		30.6	28.8
	15	30.7	29.7^
	30	30.2	31.2
	45	30.1^	30.7
24		30.6	30.6
	15	31.1	30.3
	30	31.1	31.6
	45	32.0	32.7
25		32.8	32.4
	15	32.6	32.9
	30	32.9	33.1
	45	32.7	33.8
26		32.7	34.4
	15	32.7	34.8
	30	33.2	35.1
	45	33.1	35.1
27		32.1	34.6
	15	32.5	34.1
	30	32.2	34.6
	45	32.0	34.3
28		31.0	35.0
	15	30.9	33.8
	30	31.3	32.8
	45	32.1	31.5
29		32.6	31.0
	15	33.9	30.7
	30	35.0	30.0
	45	34.1	29.6
30		34.4	30.9
	15	34.8	31.2
	30	35.5	30.4
	45	35.6	30.5
31		36.8	30.8
	15		30.6
	30		30.9
	45		31.2
32			31.2
	15		31.3
	30		31.6
	45		31.1
33			31.5
	15		31.9
	30		32.3
	45		33.7
34			34.8
	15		36.4
	30		37.8
	45		37.0

35		35.9
	15	34.1
	30	-
	45	37.0
36		37.1
	15	37.0
	30	37.0
	45	37.0
37		36.0
	15	36.3
	30	36.6
	45	38.1
38		39.4
		40.2

Appendix C Strawberry leaf temperature during sprinkling cycles in greenhouse, 1987.

Date	May 24	May 25	May 26
Time	3:00PM	2:30PM	2:45PM
Air Temps.	27-28°C	27-29°C	31-32°C

LEAF TEMPERATURE (°C)

Time Min.	Sec.			
	0	32.3	34.0	41.4
	15	32.2	34.2	41.3
	30	32.5	35.1	40.5*
	45	32.8	36.1	35.7
1		32.9	37.4	33.7
	15	32.8	38.0	32.8^
	30	32.8	38.3	32.4
	45	32.9	38.7	32.2
2		33.1	38.9	32.2
	15	33.2	39.0	32.4
	30	33.2	39.2	32.4
	45	33.6	39.3	32.5
3		33.7	39.4	32.6
	15	33.5	39.4	32.5
	30	33.3	39.4	32.7
	45	33.3	39.4	32.6
4		33.1	39.1	32.7
	15	33.3	39.2	32.6
	30	33.7	39.3	32.8
	45	33.7	39.5	32.8
5		34.1	39.7	32.9
	15	34.4	39.9	33.0
	30	34.1	39.9	33.0
	45	34.2	39.9	32.9
6		34.3	39.9	33.0
	15	34.2	40.1	33.1
	30	33.9	40.3	33.6
	45	34.2	40.2	34.6
7		34.2	40.1	34.6* ^
	15	34.1	39.6*	33.3
	30	34.1	35.7	33.3
	45	34.0	34.6	33.6

* Sprinkler turned on.
^ Sprinkler turned off.

8		34.1	33.7	33.9
	15	34.2	33.4	34.6
	30	34.3	33.0^	35.3
	45	34.2	33.2	35.5
9		34.3	33.3	35.9
	15	34.2	33.3	36.3
	30	34.2	33.4	37.0
	45	34.3	33.4	37.5
10		34.3	33.7	37.9
	15	34.4	33.9	38.1
	30	35.0	34.0	38.2
	45	35.3	33.8	38.4
11		35.2	33.6	38.7
	15	35.5	33.6	38.6
	30	35.6	33.7	38.7
	45	35.7	33.6	38.8
12		35.9	33.4	38.9
	15	36.1	33.4	39.1
	30	36.5	33.4	39.1
	45	36.8	33.6	39.2
13		37.3	34.1	39.1
	15	37.6	34.4	39.3
	30	38.1	34.8	39.3*
	45	38.4	35.0	37.7
14		38.6	35.3	34.2
	15	38.9	35.5	32.4^
	30	38.7	35.6	32.0
	45	38.6	35.7	31.8
15		38.6	34.8*	31.8
	15	38.3	33.0	31.6
	30	38.0	32.2^	31.6
	45	38.1	32.0	31.5
16		38.0	32.1	31.6
	15	38.1	32.3	31.6
	30	38.3	32.4	31.8
	45	38.4	32.5	31.7
17		38.4*	32.3	31.8
	15	35.1	32.4	31.9
	30	33.9	32.4	32.2
	45	33.2	32.3	32.4
18		32.9^	32.5	32.6
	15	32.9	32.5	33.2
	30	32.5	32.6	34.2
	45	32.3	32.7	35.1*
19		32.5	32.5	32.9^
	15	32.5	32.6	31.8
	30	32.5	32.7	31.6
	45	32.7	32.9	31.6
20		32.6	33.2	31.7
	15	32.6	33.4	31.8
	30	32.7	33.8	31.9
	45	32.9	34.1	32.2

21		32.9	34.4	32.2
	15	32.8	34.7	32.1
	30	32.7	34.9	32.1
	45	32.6	34.2*	32.3
22		32.6	33.0^	32.3
	15	32.7	32.5	32.4
	30	32.8	32.4	32.8
	45	32.6	32.5	33.4
23		32.7	32.5	34.4
	15	32.6	32.7	35.0* ^
	30	32.9	32.9	33.0
	45	33.0	33.0	32.6
24		33.2	32.9	32.3
	15	33.1	33.2	32.5
	30	33.2	33.3	32.9
	45	33.3	33.4	33.9
25		33.6	33.5	34.7
	15	33.7	33.7	35.4
	30	33.7	33.9	35.9
	45	33.4	34.1	36.4
26		33.5	34.2	36.8
	15	33.6	34.3	37.1
	30	33.5	34.5	37.3
	45	33.6	34.6	37.4
27		33.7	35.0	37.5
	15	33.9	35.4	37.7
	30	34.0	35.9	37.8
	45	34.1	36.7	37.9
28		34.1	37.2	38.0
	15	34.0	37.8	38.1
	30	34.2	38.0	38.3
	45	34.2	37.9	38.4
29		34.2	37.7	38.4
	15	34.3	37.4	38.6
	30	34.4	37.4	38.7
	45	34.4	37.3	38.8
30		34.5	37.2	38.8
	15	34.5	37.3	38.9
	30	34.6	37.4	39.0
	45	34.9	37.3	39.0
31		34.8	37.4	39.0*
	15	34.9	37.5	34.6
	30	35.1	37.6	32.4^
	45	35.2	37.7	31.5
32		35.3	37.5	31.2
	15	35.2	37.5	31.3
	30	35.1	37.4	31.2
	45	35.1	37.3	31.3
33		34.9	37.2	31.2
	15	35.1	37.2	31.4
	30	35.0	36.6*	31.3
	45	35.1	33.5^	31.3

34		35.1	32.0	31.4
	15	34.8	31.5	31.5
	30	34.6	31.1	31.7
	45	34.7	31.0	31.9
35		34.7	31.0	32.4
	15	34.7	31.2	33.5
	30	34.6	31.1	34.5
	45	34.6	31.2	34.4*
36		34.5	31.2	32.2^
	15	34.4	31.4	31.6
	30	34.0	31.3	31.2
	45	33.9*	31.3	31.5
37		34.0	31.5	31.3
	15	34.0	31.6	31.3
	30	33.7	31.7	31.5
	45	32.8^	32.2	31.5
38		32.5	32.8	31.5
	15	32.5	33.5	31.7
	30	32.7	34.5	32.0
	45	32.9	34.9*	32.4
39		32.8	33.2^	33.2
	15	32.7	32.1	33.7
	30	32.7	32.2	34.4
	45	32.6	31.8	35.0* ^
40		32.7	31.7	33.3
	15	32.6	31.6	32.3
	30	32.4	31.6	32.1
	45	32.3	31.4	32.1
41		32.5	31.5	32.2
	15	32.6	31.6	32.2
	30	32.6	31.7	32.6
	45	32.5	32.0	33.3
42		32.8	32.3	34.1
	15	32.9	32.6	34.7
	30	32.8	33.1	35.3
	45	32.6	33.4	35.8
43		32.4	33.7	36.4
	15	32.3	34.0	36.9
	30	32.3	34.3	37.4
	45	32.3	34.4	37.7
44		32.3	34.7	37.9
	15	32.3	34.9*	38.2
	30	32.3	33.9^	38.2
	45	32.7	33.5	38.4
45		32.9	34.1	38.5
	15	33.0	34.2	38.5
	30	33.0	34.6	38.6
	45	33.1	34.9	38.7
46		33.3	35.0	38.8
	15	33.3	35.4	38.9
	30	33.4	35.7	38.8
	45	33.4	35.9	38.6

47		33.4	36.2	38.7
	15	33.2	36.3	38.7
	30	33.1	36.5	38.7
	45	33.1	36.6	38.7
48		33.3	36.6	38.8
	15	33.4	36.6	38.7
	30	33.4	36.8	38.6*
	45	33.5	36.7	34.5
49		33.6	36.7	32.4^
	15	33.7	36.6	31.5
	30	33.7	36.5	31.0
	45	33.8	36.5	30.7
50		33.8	36.5	30.8
	15	33.7	36.6	30.7
	30	33.5	36.5	30.9
	45	33.7	36.4*	30.9
51		33.9	34.3	30.8
	15	34.1	32.2^	31.0
	30	34.4	31.5	31.1
	45	34.2	31.1	31.2
52		34.3	31.2	31.7
	15	34.4	31.2	32.2
	30	34.6	31.1	32.9
	45	34.8	31.2	33.7
53		34.9	31.1	34.6
	15	35.2	31.0	34.3* ^
	30	35.4	30.9	31.7
	45	35.5	31.0	31.3
54		35.9	31.4	31.1
	15	35.9	32.1	31.2
	30	36.2	32.6	31.1
	45	36.0	33.2	31.3
55		35.8	33.9	31.4
	15	35.9	34.3	31.6
	30	35.9	34.5	31.9
	45	35.9	34.9*	32.5
56		35.9	33.6	33.3
	15	35.9	31.9^	34.3
	30	35.7	31.3	34.9*
	45	35.7	31.2	32.3^
57		35.7*	31.2	31.0
	15	32.2	31.2	31.0
	30	34.1	31.4	31.0
	45	33.1	31.5	30.9
58		32.6^	31.5	31.0
	15	32.4	31.8	31.0
	30	32.4	31.9	31.0
	45	32.5	32.3	31.3
59		32.4	32.8	31.9
	15	32.4	33.3	32.6
	30	32.6	33.9	33.9
	45	32.6	34.4	34.5

60		32.4	34.8	35.0* ^
	15	32.4	34.6*	33.9
	30	31.8	32.3^	34.2
	45	32.0	31.7	34.9
61		32.5	31.5	35.4
	15	32.6	31.5	35.9
	30	32.6	31.8	36.1
	45	32.7	31.9	36.2
62		32.7	32.1	36.4
	15	32.6	32.4	
	30	32.6	32.6	
	45	32.8	33.2	
63		32.5	33.6	
	15	32.7	34.1	
	30	32.8	34.5	
	45	32.9	34.8	
64		33.0	35.0	
	15	33.1	35.3	
	30	32.9	35.6	
	45	32.7	36.0	
65		32.7	36.3	
	15	33.2	36.4	
	30	33.4	36.5	
	45	33.5	36.6	
66		33.5	36.7	
	15	33.7	36.7	
	30	32.9	36.7	
	45	32.7	36.8	
67		32.8	36.7	
	15	32.9	36.8	
	30	32.6	37.0	
	45	33.5	37.0	
68		33.7	37.0	
	15	33.6	37.1	
	30	33.8	37.2	
	45	33.7	37.0	
69		33.0	37.1	
	15	32.9	37.2	
	30	33.1	37.2	
	45	33.2	37.3	
70		33.3	37.3	
	15	33.6	37.3*	
	30	34.1	35.6	
	45	34.8	33.2^	
71		35.3	31.8	
	15	35.4	31.3	
	30	35.6	31.2	
	45	35.9	31.2	
72		35.7	31.4	
	15	35.9	31.5	
	30	35.8	31.4	
	45	36.1	31.6	

73		35.9	31.5
	15	36.1	31.4
	30	36.3	31.5
	45	36.3	31.5
74		36.4	31.5
	15	36.1	31.4
	30	36.2	31.6
	45	36.2	31.5
75		36.2	31.7
	15	36.3	31.9
	30	36.4	32.0
	45	36.4	32.1
76		36.4	32.3
	15	36.2	32.5
	30	36.1	32.9
	45	36.1	33.3
77		36.2	33.9
	15	36.1*	34.4
	30	34.3	34.8*
	45	33.0	33.9
78		32.4^	32.0^
	15	32.1	31.2
	30	32.0	31.2
	45	32.2	31.4
79		32.3	31.4
	15	32.4	31.4
	30	32.4	31.4
	45	32.7	31.3
80		32.6	31.4
	15	32.6	31.7
	30	32.5	31.6
	45	32.7	31.7
81		32.8	31.9
	15	32.8	32.1
	30	32.8	32.3
	45	32.9	32.5
82		33.0	32.9
	15	32.9	33.4
	30	33.1	33.7
	45	33.1	34.1
83		33.4	34.4
	15	33.2	34.7
	30	33.5	34.9*
	45	33.6	34.4
84		33.3	32.8^
	15	33.3	32.1
	30	33.3	31.4
	45	33.2	31.4
85		32.9	31.4
	15	33.0	31.5
	30	33.3	31.5
	45	33.8	31.5

86		34.1	31.6
	15	34.1	31.6
	30	34.2	31.7
	45	34.3	31.8
87		34.6	31.9
	15	34.9	32.2
	30	35.0*	32.3
	45	34.4^	32.5
88		33.8	32.7
	15	33.7	32.9
	30	33.8	33.4
	45	33.9	33.9
89		34.0	34.7
	15	34.0	
	30	34.0	
	45	34.0	
90		34.0	

STUDIES IN HIGH TEMPERATURE STRESS OF STRAWBERRY AND ALLEVIATION OF STRESS THROUGH EVAPORATIVE COOLING

by

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Abstract

Critical high temperatures that inhibit strawberry (Fragaria x ananassa Duch.) fruit development and runner (stolon) growth were investigated. Duration and frequency of water applications were also studied to develop irrigation scheduling procedures for evaporative cooling.

In growth chamber studies, a critical high temperature range that reduced berry fresh weight and runner growth was between 35/25°C and 40/30°C (15hr day/9hr night). Air and plant temperatures were similar under these conditions. In field studies, it was noted that leaf temperature may be as much as 17.5°C higher than air temperature on sunny days. Monitoring plant temperature, therefore, would be a better indicator of the need for stress alleviation.

Sprinkler irrigation was effective in reducing strawberry leaf temperature by as much as 15°C within 3 minutes. Amount of temperature reduction and duration varied with wind speed, degree of cloudiness, and relative humidity. At high relative humidity and low wind speed, minimal evaporative cooling occurred. This increased the duration of fruit wetness, reduced fruit firmness, and thereby increased the probability of fruit rotting diseases.